



# LEARNING TO INNOVATE ACROSS DISCIPLINES

This is a student-led paper summarizing a case study on how present-day engineering students learn what is needed to innovate solutions while going well beyond what is usually taught in course lectures. It is set in the context of an aerospace engineering school in an American university, with typically large class sizes and a school culture that emphasizes research and instruction.

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A CASE  
STUDY ON  
THREE TEAM  
PROJECT  
EXPERIENCES

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# Abstract

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This is a student-led case study on how present-day engineering students learn what is needed to innovate solutions, going well beyond what is usually taught in course lectures. It is set in the context of an aerospace engineering school in an American university, with typically large class sizes and a school culture that emphasizes research and instruction. Three projects are included in the study, progressing in level of complexity. There was some commonality in participants between the three. The first is a large open-ended advanced concept development exercise in an upper-division course. The second is a Capstone Design course. The third is a professional society's international level vehicle design team competition. The results show where and how students acquired the knowledge, skills, confidence and experience to build through the years and reach a level where they could innovate and perform with excellence at the level of the international competition. The case study is aimed to benefit instructors who are interested in improving the depth of their courses as well as improving their students' ability to innovate in a meaningful way.

## Introduction

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The case study described in this paper examines a vertical sequence of experiences where students learned to innovate with rigor and depth, broadened their horizons by applying the skills that they learned, and then went on to compete successfully against the best from around the world, in an arena demanding innovation with depth. These students advanced through the curriculum at the School of Aerospace Engineering, Georgia Institute of Technology. Each student learned to deal with uncertainty when innovating, exploring outside their disciplines, and satisfying common sense while thinking outside the box. Most importantly, students learned to work in a team where self-discipline, initiative, and leadership traits are developed.

There is a critical need to build excellence<sup>i,ii</sup> and enable our best students to perform much better than their predecessors. The case study documents the progression of the students' learning from a core engineering course, to the capstone design experience, and on to the intensely challenging environment of an international design competition.

The open-ended course assignment involved the conceptual design of a missile defense system for the continental United States with particular focus on aerodynamics aspects. Students were divided into teams of two and given six weeks to complete the assignment with mandatory weekly reporting. Discussion and integration of course material was learned just in time to do the high speed aerodynamics portions of the project. Thus, the learning for this project was integrative. Students had to investigate current technologies, available programs and make engineering judgments to design an advanced concept system where there is no precedent in the published literature. The capstone design course is part of the core curriculum. Here students learn to work in an environment similar to that in industry. Emphasis is on learning the principles and processes of design, and the workplace issues of working in diverse teams. The third case is an international vehicle design competition held annually under the auspices of an international professional society.

## Open Ended Project

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### [Project Breakdown](#)

A short primer on strategic defense issues was given in the high speed aerodynamics course to set the context for this particular assignment. These issues began with the Cold War concept of Mutually Assured Destruction (MAD), the treaties on anti-ballistic missiles and space weapons, the Strategic Defense Initiative (SDI), the end of the Cold War, and the rise of other threats leading up to the present, with upcoming capabilities and threats discussed. The objective of the project was to create

a solution for a defense system for the specific case of an attack from an intercontinental ballistic missile (ICBM). The premise is that in times of tension, some aircraft would patrol at about Mach 0.6 and 40,000 feet, offshore and over the US.

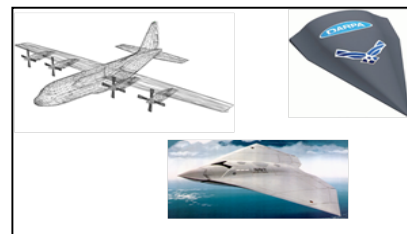
The system was composed of a transonic patrol, a supersonic unmanned combat air vehicle (UCAV), and a hypersonic weapon. The large transonic patrol would carry the other two components. Up to four uninhabited combat air vehicles (UCAV's) can be launched on warning from the carrier. Several such carriers would fly over the periphery of the US at an efficient altitude of 40,000 ft (~12,000 meters). The supersonic UCAV would accelerate and climb up to altitudes of 150,00ft (~46,000 meters) in order to put its four hypersonic weapons, at an appropriate altitude with time left to hit the incoming warheads. The supersonic UCAV's are expected to accelerate to Mach 4. The UCAVs would then glide to landing. The air breathing supersonic-combustion ramjet hypersonic weapons would quickly accelerate to collide with any incoming warheads. Teams of two students each were formed. Weekly reports updating the team's progress were expected.

### Teams and deliverables

Teams of two individuals were formed where weekly reports updating the team's progress were expected. The end result, due at the end of the semester, was left to be open ended. This allowed for an innovative solution that was directly dependent on the effort of each set of students. Grading was strictly based on the professor's judgment of the student's efforts.

### Parameters Studied

The performance parameters studied were the total weight, range, endurance, maximum speeds, critical Mach number, lift to drag ratio, service ceiling, rate of climb, turn rates and radius, and drag estimates. A schematic illustration of the different types of vehicles involved in the design is shown in

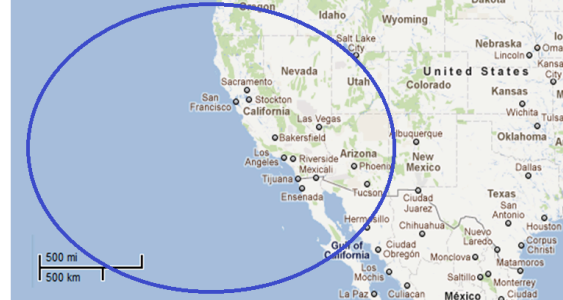


**Figure 1: Schematic illustration of the 3 vehicles**

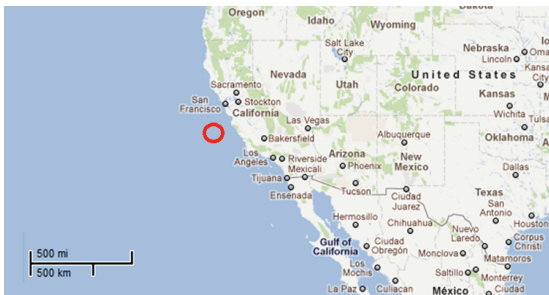
Figure 3. The carrier aircraft is likely to be much bigger and powered by turbofan engines, unlike the smaller turboprop aircraft shown.

## Results

From the calculations performed, the team was able to calculate the range of this aircraft. From this range of 11 km at Mach 0.8, the team estimated of the area that this transonic patrol will be able to cover. From figure 5, it is easy to see that this aircraft will be able to loiter at an area that is substantially big. This is good since the plan is to have more than one aircraft monitoring around the coast line and beyond at the same time.



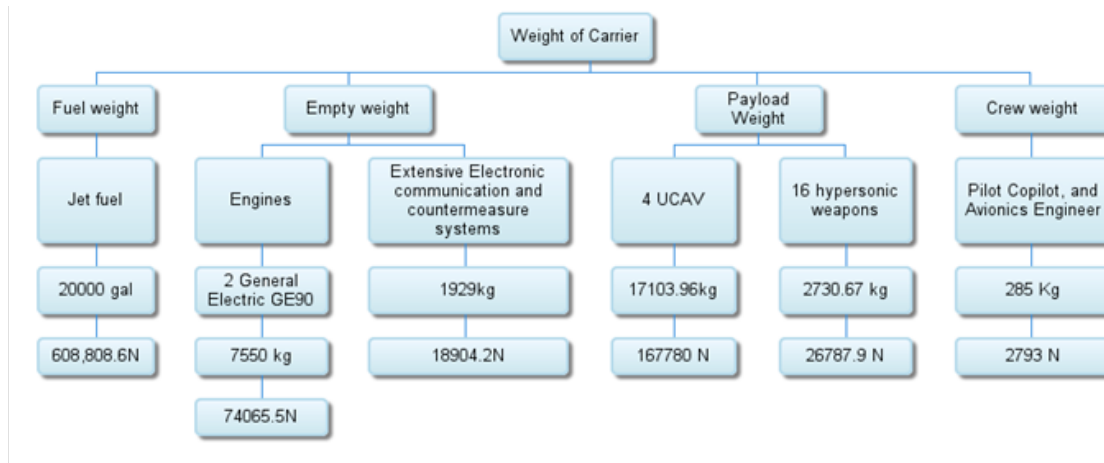
**Figure 2: Area coverage issues**



**Figure 3. Two minute area coverage**

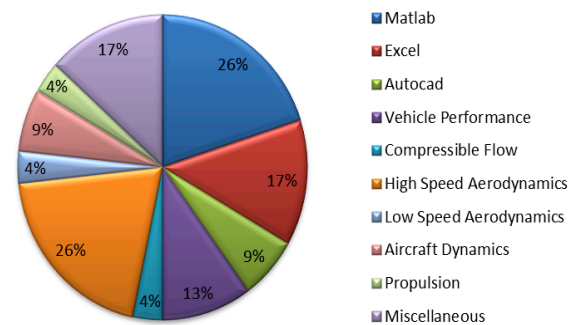
As a stated requirement, the team also calculated an average area that the transonic patrol would cover given a two minute warning to launch the UCAV's. In this two minute period, the aircraft is assumed to be going the opposite way and turn around and follow the ICBM. The area that the patrol would cover was found by integrating the velocity of the transonic patrol with respect to time from zero to 120 seconds, which is the two minute warning.

An estimated weight breakdown of the complete system was developed and shown by figure 7 below. The complete system includes the transonic patrol's fuel and crew weight, its empty weight, the weight of 4 UCAV's and a total of 16 hypersonic weapons.



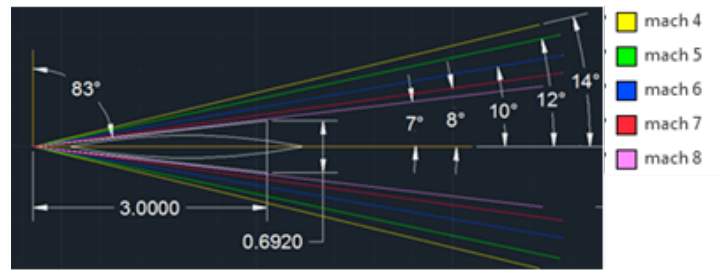
### The Engineer's Toolbox

Several courses and tools were used throughout this project in order to facilitate and perform the required analysis in the given amount of time. Figure 5 is an estimated visual representation of the many tools and courses used ranked in percentages based on their use during the development of the defense system.



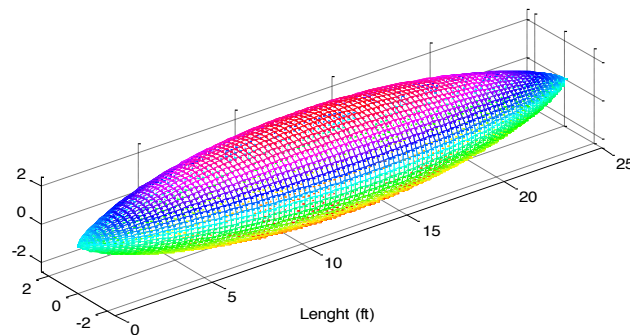
**Figure 5. Courses and tools used in the conceptual design of the defense system**

Some particular examples include the knowledge and skills developed in the drafting course with AutoCAD in ME 1770, while using knowledge from Compressible Flow to find Mach angles. This mixture of unrelated knowledge allowed for quick analysis while obtaining “ball park” numbers regarding the shape and size of the defense weapon. Figure 1 shows how a particular team sized the shape of the defense weapon, taking into account Mach angles in order to reduce shocks on the body's structure.



**Figure 6. Defense weapon showing shock angles for different Mach numbers**

Once an idea of the defense system was obtained it was time to mix the knowledge gained from the high speed aerodynamic course with another one of our engineering tools, MATLAB. Thus, the airframe was designed for minimum drag and a high speed body with the lowest aerodynamic wave drag was produced using mixing the knowledge from the two courses. The Sears-Haack body is shown through Figure 2.



**Figure 7. Sears-Haack body produced using Matlab**

This process was then extrapolated to other components of the defense system, such as the supersonic drone that would be expected to carry multiple defense weapon systems and its carrier. Having weekly reports not only encouraged students to keep up with the material in class but to go beyond and learn as much as possible in all aspects of this field.

### Student Thoughts

It is well understood that this type of project represents a similar experience to what students will experience in the real world. It allows for each team of students to use every source of knowledge available, while learning to integrate unfamiliar material.



In this case, the unfamiliar material came from the high speed aerodynamics course as it was being taught throughout the semester. Thus, students were forced to go well beyond what is learned in a classroom. Open ended projects teach students how to begin making “back of the envelope calculations” and decisions well before a final configuration solution is known. This in turn pushes students to pull tools out of their “engineering toolbox”, which has been growing since the beginning of their education.

## Capstone Project

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### [Course Breakdown](#)

The capstone course at Georgia Tech is a two semester, 8 hour academic credit course, that constitutes the culmination of four years of engineering education. Thus, it is here where students learn to bring their ideas together. In the aerospace department all seniors must choose rotorcraft, fixed wing, or space as their senior capstone course. For the purpose of this paper, the experience is based on that of rotorcraft design.

The sole purpose of the capstone course is to pull every skill together and apply them towards the design and implementation of a product. Another important purpose of this course is to provide the students an opportunity to experience team-based design under conditions that closely resemble those that will be encountered in industry. It is here where students will get exposed to an experience in which they have to specify, design, and produce a full-system beginning from relatively ill-posed needs as stated by a customer.

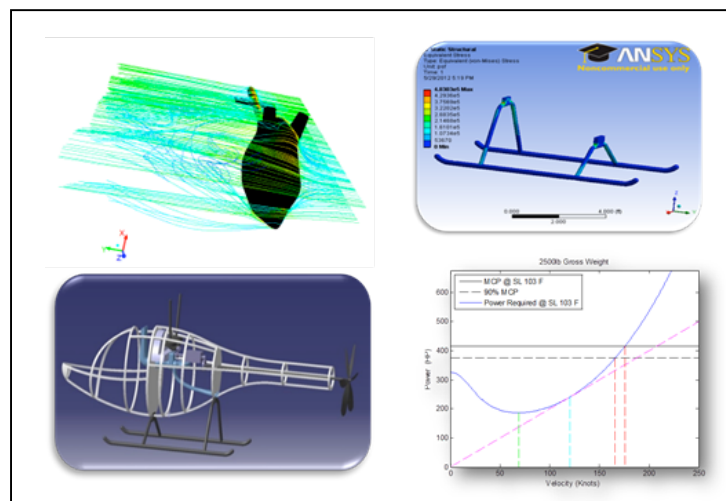
The first semester of the course focuses on teaching students the fundamentals of helicopter theory. The individual project involves sizing a helicopter given a set of requirements and mission. Some of the skills acquired by students fall in the traditional areas of aerospace engineering such as Thermodynamics, Fluid Dynamics, Structural Mechanics, 3-D Solid Modeling and Vehicle Performance to mention a few. Each week, a mandatory three hour lab is held by an expert in order to focus on a particular field of study. These sessions allow for each student to find an area in which their interests fall

under. The ultimate goal is that the student will find a field and become an expert in it in order to become an asset to their team. Table I shown below is a breakdown of the labs offered throughout the first half of the course.

**Table I. Subject areas and skills involved in the Capstone Design course**

3D Modeling	Structural Analysis	Cost Analysis
Computational Fluid Dynamics	Rotor Dynamics	Stability and Control
Flight Simulation	Design	Optimization

An example of these technical skills is shown through Figure 7. This figure contains visual representations of some of the tools used in industry to produce high fidelity results. Computational fluid dynamics flowing through the fuselage of a helicopter using Fluent is shown in the top left corner. Finite element analysis performed on the landing gear of a helicopter to ensure the structural integrity and load paths using the ANSYS software<sup>iii</sup> is shown in the top right corner. 3D modeling of a helicopter structure using Catia is shown in the left bottom corner, and a performance analysis of a helicopter using momentum theory using MATLAB is shown in the right bottom corner.



**Figure 7: Several screenshots of software learned in the capstone design course**

## Grading and Student Assessments

Each student's grade is based on a combination of personal and team performance goals. Individual assignments and laboratory assessments compose part of the students' grade. However, in order to graduate, each student must prove that not only he or she is capable of completing individual assignments, but can successfully work in a team where their performance is assessed by every member of the team. Students must also develop and sharpen skills in team organization, time management, self-discipline, and technical writing in order to be successful not only in this course, but in their careers as well. Some of the non-technical skills exercised in this course include: presentation skills, project planning, work breakdown structure and division of labor, record keeping, self-initiative, motivation, identifying customer needs, concept selection, and most importantly the ability to pursue a design under conditions of shifting requirements.

# International Design Challenge

## Challenge breakdown

The American Helicopter Society's, (AHS), 29th annual student design competition request for proposal (RFP), sponsored by Sikorsky, stipulated the desire for a lightweight, highly maneuverable rotorcraft system. This rotary wing pylon racer was expected to perform at levels similar to the fixed-wing red bull competition aircraft, in order to spark interest in a helicopter racing sport. Fitting well with the rotorcraft design capstone course, a team of students who were enrolled in the rotorcraft design capstone course was formed and an innovative solution to this proposal was initiated.

The scoring function given by the RFP is a combination of time, fuel weight, and engine power given by Equation (1). Thus, careful consideration was taken at each step of the design process in order to strike a balance between fuel efficiency, engine power, load factor, and speed, all while maintaining safety for the pilot and spectators.

$$\eta = 2 * CourseTime[sec] + 5 * Fuel_{consumed}[lbs] + MRP_{S,L,ISA,Uninstalled}[SHP] \quad (1)$$

According to the RFP, the three most stringent requirements are that the helicopter must be sized to successfully hover at 103°F at Sea Level, achieve a minimum of 60 knots sideward flight, and achieve a minimum of 125 knots at 90% MRP at 103°F at Sea Level. The course, however, is assumed to be flown at 80°F at Sea Level since the race is assumed to take place in autumn. The track is separated into 10 different sections starting at the stage grounds and ending at the finish line, see Figure 8. At the staging grounds (a local football field), the helicopter must be able to fit in between the 40 yard



**Figure 8. Illustration of the course over the Hudson River**

lines when stationed at the 50 yard marker. There must be a minimum of 1 rotor radius clearance or 15 ft radius from all rotating components for ground crew safety. The 225lbs pilot has 10 minutes to warm up and 5 minutes to takeoff. The pilot is required to start the course at no more than 100 kts. Then, the helicopter is required to perform 6 different maneuvers throughout the track. The full list of the racetrack course is displayed below.

**Table II. Complete list of mission segments**

Segment	0	1	2	3	4	5	6	7	8	9
Maneuver	Staging	Start	Slalom	Short Stop	Straight Away	Quad Pylon	Slalom	Hover, Pirouette Pickup	Side Flight	Finish
Altitude	<200 ft AGL	<200 ft AGL	<200 ft AGL	<500 ft AGL	<200 ft AGL	<200 ft AGL	<200 ft AGL	Sea Level	<200 ft AGL	<200 ft AGL
Temp	80°	80°	80°	80°	80°	80°	80°	80°	80°	80°

Each maneuver requires a certain amount of maneuverability and agility from the helicopter. For example, the slalom sections represent a series of sustained turns that require the helicopter to have a high maximum sustained load factor and a high roll quickness and control power characteristics at high airspeeds. The Hudson River course was broken down into 9 maneuvers and analyzed to determine the critical helicopter

design parameters which would contribute the most toward reducing the overall course completion time. Speed, turning radius, load factor, control power, and acceleration/deceleration clearly became the most important characteristics for this racing rotorcraft. A detailed breakdown of all of the requirements found in the RFP was developed. They are separated between performance, mission, and miscellaneous requirements.

#### Team Dynamics

The Badger's design team was an international alliance between nine undergraduate students and three graduate students, for a total of twelve engineering students. The team of students was mentored by Dr. Daniel Schrage and Dr. Ilkay Yavrucuk. Since it was of importance to keep the team's momentum going from the beginning, weekly meetings were held every Thursday evening. These meetings were specifically designed so that students could discuss their progress and brainstorm problems together. Each student's voice was heard equally. International students were able to join student meetings in the form of video calls through the Skype software.

The team divided the work equally based on the interests and experience of each student. A team leader and a chief engineer were assigned in order to maintain order in the group. The job of the team leader was to arrange meetings and analyze the team's progress through the use of a progress chart while the job of the chief engineer was to oversee the entire design, assist students in their endeavors, and finalize the technical paper. Monthly in-progress reviews (IPR's) were held where both the team leader and the chief engineer were in charge of creating a professional presentation of their current work. Every member of the group was required to attend this meeting and time arrangements were made in order to accommodate the international students due to the shifted time zones. During every meeting, a set of designated experts and professors posed as judges. Their jobs were to question, critique and evaluate the team's progress. At the end of each meeting, judges gave key points that they wanted to see for next month's review.

## Examination of Different Configurations

As with the design of any aircraft, it is important to determine what vehicle configurations provide the capability to perform the desired mission profiles. The team, therefore, decided to examine and compare the capabilities of the conventional helicopter, compound helicopters, tandem rotor helicopters, coaxial and intermeshing helicopters. In order to generate the advanced rotorcraft concept, a morphological matrix was generated. Table III below shows that a total of 77,760 configurations options are available. From there, the list was narrowed down to 4 different configurations and a baseline model was chosen as shown in Table IV.

**Table III. Morphological Matrix**

Category	Options						No. Conf.
Rotor	Rotor Configuration	Single Main / Tail Rotor	Coaxial	Intermeshing	Tandem	Tilt	5
	Number of Blades	2	3	4	5	---	4
	Hub type	Articulated	Bearingless	Hingeless	Teetering	---	4
Configuration	Compound	Wing	No wing	---	---	---	2
	Vertical Stabilizer	Single	Dual	None	---	---	3
	Horizontal Stabilizer	Tail	Canard	None	---	---	3
Propulsion	Type	Rotor Only	Pusher Prop	NOTAR	---	---	3
	Number of engines	1	2	---	---	---	2
Landing gear	Type	Skid	Retractable	Water landing	---	---	3
Control	Type	Hydromechanical	Fly by wire	Fly by light	---	---	3
Total # of possible Configurations							77,760

**Table IV. List of Chosen Configurations**

Category		Baseline	1st Conf.	2nd Conf.	3rd Conf.	4th Conf.
Rotor	Rotor Configuration	Single Main	Coaxial	Intermeshing	Single Main	Intermeshing
	Number of	4	4	3	3	2

	Blades					
	Hub type	Teeter		Teeter	Articulated	Teeter
Configuration	Type	No wing	No wing	No wing	No wing	No wing
	Vertical Stabilizer	Dual	Single	Single	Single	Single
	Horizontal Stabilizer	Tail	Tail	None	Tail	Tail
Propulsion	Type	Rotor Only	Pusher Prop	NOTAR	Rotor Only	Pusher Prop
	Number of engines	2	2	1	1	2
Landing gear	Type	Skid	Retractable	Retractable	Retractable	Skid
Control	Type	Hydromechanical	Fly by wire	Fly by wire	Fly by wire	Fly by wire

Once the chosen configurations were known, it was time to begin looking at the best one in order to begin an optimization analysis.

### Analytical Hierarchy Process

“The secret to producing a successful helicopter is to let the requirements drive the design. When one comes in with an idea of a pre-design and attempts to tweak it for a successful requirement completion, one simply ends up with the wrong answer.” – Steve Weiner (Sikorsky).

The previous words are quoted from one of the first design meetings where Steve Weiner was invited to be a guest speaker and advise the group. Mr. Weiner was the Chief Engineer for the Sikorsky X-2 and one of the 10 most brilliant innovators of 2009 according to Popular Mechanics. Thus, his words were kept in mind during the development for the design of what is now Georgia Tech’s first intermeshing rotary wing racer.

Establishing the evaluation criteria is therefore the first step in the analysis of the RFP requirements. Each requirement must be evaluated on their relative importance against the others. In order to determine what concept meets the objectives of the top level requirements, an analysis of different vehicle configurations is required. In order to evaluate the different concepts and determine how each one of them meets the requirements, the Analytical Hierarchy Process (AHP) was used. Six different design

criteria were chosen to represent the objectives of the RFP. These were then ranked based on the voice of the customer through a prioritization matrix as shown in Table V.

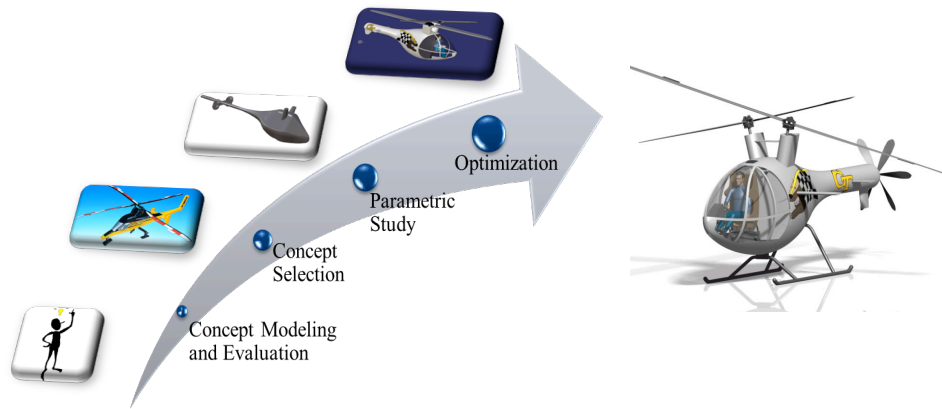
**Table V. Prioritization Matrix**

	Time	Fuel Burned	MRP	Safety Index	ACQ Cost	Operational Cost	Rank	RMS Fraction	Norm %
Time	--	0.4	2	2.5	3	3	10.9	49.28%	24.0%
Fuel Burned	2.5	--	5	2.5	3	3	16	72.34%	35.2%
MRP	0.5	0.2	--	2.5	3	3	9.2	41.59%	20.2%
Safety Index	0.4	0.4	0.4	--	1.2	1.2	3.6	16.28%	7.9%
Acquisition Cost	0.33	0.33	0.33	0.9	--	1	2.9	13.11%	6.4%
Operational Cost	0.33	0.33	0.33	0.9	1	--	2.9	13.11%	6.4%

These four possible configurations were then subjectively evaluated with respect to these normalized weighted values based on engineering estimates and historical data. To help with this rating process, the single rotor configuration was used as the baseline, and the other configurations were evaluated based on whether they perform better or worse in each area.

Combining the configuration comparison and the relative importance of each quality, TOPSIS, Technique for Order Preference by Similarity to Ideal Solution, was used to select an optimal configuration for the mission requirements based on an indisputable ranking method. TOPSIS involves defining “ideal” and “least ideal” configurations as the best/worst cross-configuration values for each characteristic. The ideal configuration values are normalized for each characteristic by the RMS for that characteristic.





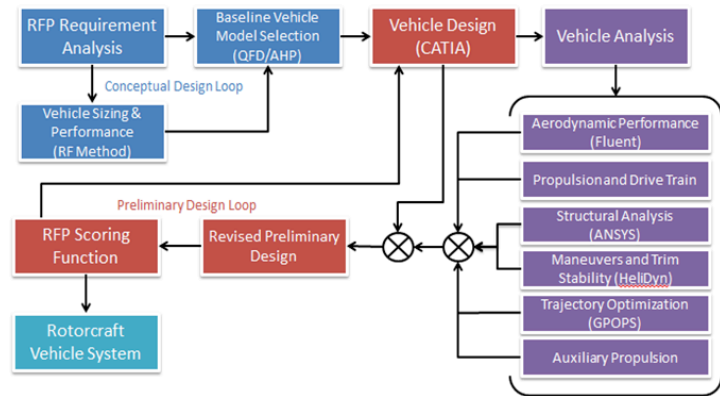
**Figure 9. Design Process Flow Map**

Radar plots were used to graphically show how given designs perform against the various criteria such as operational cost, acquisition cost, safety index, MRP and time. The next step in TOPSIS selection is to determine how close each configuration is to the ideal and how far each configuration is from the worst. Based on the TOPSIS methodology and engineering estimates, the intermeshing rotor configuration was chosen as the best fit for this particular mission. The coaxial rotor was a very close second. The preliminary design led to the intermeshing design concept, aiming to score on the RFP's originality grading criterion. This design is the first synchropter design to come from Georgia Tech and is unconventional for highly maneuverable aircraft. All things considered, it was concluded that the intermeshing design was the most original and optimal configuration for this mission and competition. The design process flow map is illustrated in Figure 9.

### Integrated Product/Process Development (IPPD)

In the conceptual design procedure, the IPPD methodology assists the designers in investigating the requirements set by the RFP and attaining promising solutions. The IPPD works by organizing the very iterative design process in a systematic way. Normal IPPDs contain four loops: the conceptual design loop, initial product data management loop, preliminary design iteration loop, and the process design iteration loop.<sup>vi</sup>

The process starts with analyzing the requirements set by the RFP and selecting a baseline model. An RF (required fuel) method is then used to size the baseline vehicle. After the vehicle's size was assessed, the even more iterative process of analyzing the individual components



**Figure 10. IPPD Design Methodology Flow map**

began. Several trade studies were completed. Examples of these are basic helicopter configurations, auxiliary propulsion types, main rotor airfoils, hub configuration and transmission selection. Once the most ideal solutions were obtained and integrated within the CATIA model, the revised design was scored using the RFP overall evaluation criteria (OEC) shown by Equation (1) above. This process was repeated until the minimal OEC was achieved thereby marking the final design. The Badger's final score is 1380.6.

#### Performance Results and Specifications

The Badger design outperforms RFP performance requirements with the use of auxiliary propulsion in the form of a pusher propeller for both increased acceleration and deceleration properties. Modified model was based on Leishman's model for tandem rotors.vii

**Table VI. Performance Summary**

Parameter (103F)	GW = 2500lbs	GW = 2800lbs
Best range speed	119.83 knots	123.56 knots
Best endurance speed	68.58 knots	73.12 knots
Maximum speed	175.87 knots	174.27 knots
Speed at 90% MCP	165.73knots	164.13knots

It offers 176 kts maximum speed at 103F temperature, 60kts in sideward flight, 166kts maximum speed at 90% maximum MCP, and hovers at sea level on a 103F day with a

300 lb payload. Table VI above summarizes performance while Table VII below is the summary of the overall specifications of The Badger.

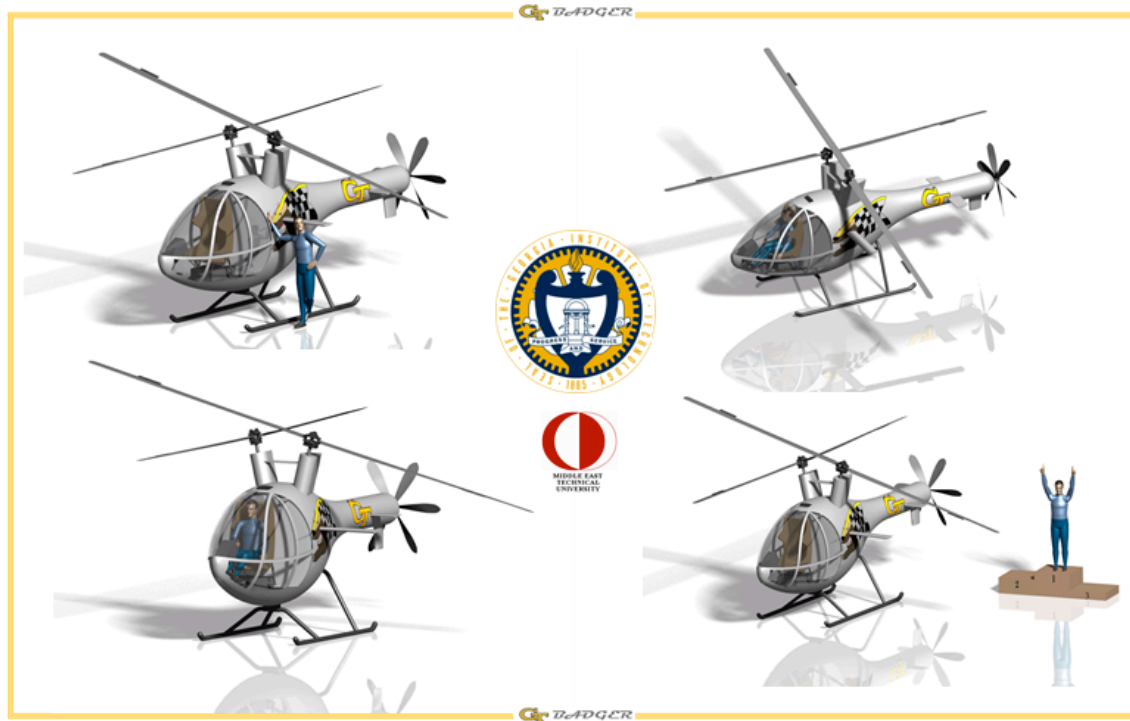
**Table VII. Specifications Summary**

BADGER SPECIFICATIONS			
WEIGHTS	Units	Value	
Empty Weight	lbs	2148	
Max. Gross Weight	lbs	2800	
GTOW	lbs	2500	
Payload	lbs	300	
Max. Fuel Weight	lbs	127	
PERFORMANCE @ S.L. 103 F	Units	GW 2500 lbs	GW 2800 lbs
Max. Cruise Speed	kts	175.9	174.2
Speed at 90% MCP	kts	165.7	164.1
Best Range Speed	kts	119.8	123.6
Best Endurance Speed	kts	68.6	73.1
Max. Sideward Flight Speed	kts	65.5	37
Max Sustained Load Factor	G	3.11	-
Course Time	s	247.8	-
POWER PLANT	Units	Value	
Number of Engines		1	
MRP @2 min 103°F S.L	hp	550	
MCP @ 103°F S.L	hp	424	
GENERAL DIMENSIONS	Units	Value	
Number of Blades (per rotor)		2	
Main Rotor Diameter	ft	24.8	
Main Rotor Blade Chord	ft	0.66	
Main Rotor Disk Loading	lbs/ft <sup>2</sup>	2.58	
Tip Speed	ft/s	670	
Propeller Diameter	ft	6	
Flat Plate Area Forward Flight	ft <sup>2</sup>	7	
Flat Plate Area Sideward Flight	ft <sup>2</sup>	41	

## Final Product

The RFP required a more maneuverable rotorcraft than arguably any rotorcraft made before. This proposal presented the conceptual, preliminary, and final design process of an extremely unique rotorcraft. Through several iterations of the design

process focusing on maneuverability, this configuration has become an effective racer. Because The Badger was designed with maneuverability in mind, it is an effective racing rotorcraft. Not only does the Badger meet the criteria stated, but it also successfully outperforms the competition. Figure 11 shows the final rendering of the successful design that won the \_\_\_th international student design competition.



**Figure 11. Final Rendering of International Design Winner**

## Discussion of Educational Aspects

As stated at the outset, this is a case study tracing what a team of students who shared common experiences did in a vertical subset of the curriculum and beyond in the general area of technical innovation. Two of the experiences were parts of regular coursework, but tuned to bring in innovation towards advanced concepts. The third was an international competition that used the learning from the prior courses in an intense real-world competitive setting, contributing its own learning. A reviewer of the abstract

of this paper demanded to know the educational value and the scientific method in this work. The educational questions ask how students learn to innovate at the level of the international competition, where they learn the habits that lead to bold innovation across disciplines, accompanied with in-depth, rigorous analytical skills. The scientific methods applied are in developing the curricular experience that allows students to learn and perform far beyond what was possible even a few years ago. In upper level courses, the number of students decreases significantly than that of the core courses. Thus, the most useful scientific approach is to examine the performance of these students and obtain their own introspections of what worked.

## Technical Depth

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The aerodynamics course AE3021, like the rest of the core curriculum, was focused on subject area depth. The AE3021 course provided an advanced concept development exercise to integrate the subject knowledge. Perhaps for the first time in the curriculum for these students, a course expected students to bring in knowledge and skills gained in other courses and merge it with their explorations of new areas in order to synthesize a new conceptual design in a completely new area. Thus in this course, the technical depth needed to make innovations was emphasized.

The capstone design experience further educated the students in the lore, terminology, methods and practices of aircraft design. As seen from the work presented, this included system design and optimization methods. Thus, students now had the capability to bring design tools into their repertoire, making the innovation process more systematic.

The design competition experience gave students the intense practical experience of making the innovation process highly quantitative, and “letting the requirements drive the design” rather than depend on just intuitive innovation. This closes the cycle, now equipping the students with the depth, the tools and the quantitative metrics to conduct engineering innovation.

# Breadth of Domain

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The students got early exposure to the need for breadth when they had to consider various issues including strategic deterrence history and global military realities, in the course assignment. The capstone design course required them to bring in several considerations to meet the design requirements, and learn to use professional-level tools in several disciplines simultaneously. The design area taught them how to consider the entire design space and a large number of possible configurations, while systematically narrowing down to a final design.

# Non-Technical Skills

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The single and twin team assignments in the aerodynamics course and the individual performance assignments in Rotorcraft Design demanded individual initiative. The two-person teams in AE3021 demanded communications and coordination, and this was expanded to the larger (5 to 10) teams in the Capstone Design course. Students had to deal with team dynamics, and learn the communication skills needed not only to get work done in teams but to interact with the rest of the class and the reviewers through their work.

# Conclusion

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The three projects together had one goal in common: Prepare the next generation of aerospace engineers to deal with uncertainty when innovating new solutions to problems that have never before been looked at. Within the constraints of a standard engineering curriculum, the depth, breadth, tools and quantitative metrics needed to conduct innovation within a large system context, are all successfully conveyed.

The paper conveys the sequence of learning needed for successful innovation. First, depth in technical subjects is conveyed through core engineering courses, along with a free-form exploratory experience of advanced concept design. In the capstone design course, the process of design is codified so that students can organize their approach much better in the design process. The experience of international level design competitions, in teams including both graduate and undergraduate students, then allows the students to grasp and use professional-level tools along with quantitative metrics to allow the requirements to drive towards a winning design, providing the students with the background and confidence to practice innovation in real life situations.

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